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Letter to the Editor

# Network approach to modeling and simulation of solar photovoltaic cell

A R T I C L E I N F O

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A B S T R A C T

The cost and performance of PV plants goes with the module under consideration. However the electrical parameters of the modules vary from those provided by the manufacturer with the ageing of the module. Therefore, the behavior of the mathematical model of a PV module cannot match the real operating conditions. There are papers having proposed an improved model of a PV module that makes use only parameters provided by manufacturer's datasheets without requiring the use of any numerical methods. This paper aims to interpret by using one of the available models represented as Norton's equivalent circuit which is a simple and approximate model. Norton's circuit model representing the module helps knowing the behavior of solar module. The study and performance of this model is compared with that of the existing model using Matlab and the results are matching to the greater extent. The results obtained for both the models are validated by conducting series of experiments on a physical module. Thus, the work signifies yet another model for a PV module to evaluate the performance parameters



## 1. Introduction

Radiant light and heat from the sun, has been harnessed by human society since ancient times using range of ever evolving technologies. Solar radiation, along with secondary solar powered resources such as wind and wave power, hydroelectricity and biomass, accounts for most of the available renewable energy on the earth. India receives solar energy equivalent to over 5000 trillion KWh per year. The daily average solar energy incident varies from 4–7 KWh per square meter depending upon the location. Only a minuscule fraction of the available solar energy is used [1]. The MNRE (Ministry for New and Renewable Energy sources) has announced a new initiative on development and demonstration of MW capacity grid interactive solar power generation in January 2008, with a view of harness the vast solar energy potential in the country for power generation. Under the program, MNRE will support grid interactive solar power generation projects up to a maximum capacity of 50 MW [2].

Renewable energy generation system, based on photovoltaic (PV) modules, is the most suitable solution, in particular for domestic power levels. This locally available resource will reduce $CO_2$ emission and the energy consumption produced by conventional resources. The cost and performance of PV plants strongly depends on modules.

## 2. Literature review

The electrical parameters can vary with the prolonged use and may not match with the parameters mentioned there on the manufacturer's data sheet. Therefore, the behavior of the mathematical model of a PV module cannot match the real operating conditions. The literature survey reveals that lots of work has been carried out by researchers and have developed quite a good number of models of PV modules. [3–7,9–11]. The double-diode model [3] is the most accurate model, but it is quite complex due to the presence of a double exponential and six parameters to involve. A different model, based on a single diode circuit, was then proposed in [4,5] shown in Fig. 1. In both cases, the mathematical models require the knowledge respectively of six and five parameters that are not directly available on manufactures datasheets. Finally a model with all parameters achievable from manufacturer's datasheet is [8] is used here to interpret PV module as the Norton's equivalent circuit.

## 3. Proposed work

The model [8] is used as a reference to represent a PV module by Norton's equivalent circuit consisting of current source dependent on irradiance & temperature and a resistance in parallel with the dependent current source. The study is carried out in three stages using MATLAB for simulation of the models.

1) The model [8] is used to verify the effect of irradiance and temperature on the PV module (PW75-21) characteristics by simulation.
2) Interpretation of model [8] as Norton's equivalent circuit and consequences on the characteristics.
3) An experiment is conducted on the installed PW75-21 PV module and the *I*–*V* characteristics along with power curve are obtained. This is done to assert the behavior of the PV module.

## 4. Methodology

The details of the mathematical model [8] is given here, as the same is taken as the reference model for performance comparison

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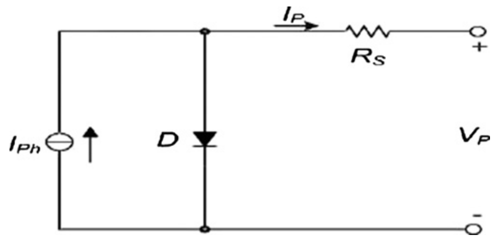


**Fig. 1.** Single diode equivalent circuit of a PV cell.

in this work. Model simulation using MATLAB and experimentation is carried out to validate the proposed model.

*4.1. A model [8]:*

Current of a PV module can be expressed as function of voltage, by the expression derived from [6]:

$$I_p = I_{SC}\left[1 - C_1\left(e^{\left(\frac{V_P}{C_2 V_{OC}}\right)} - 1\right)\right] \tag{1}$$

where

$$C_1 = \left(1 - \frac{I_{MPP}}{I_{SC}}\right) e^{\left(\frac{-V_{MPP}}{C_2 V_{OC}}\right)} \tag{2}$$

$$C_2 = \frac{\left(\frac{V_{MPP}}{V_{OC}} - 1\right)}{\ln\left(1 - \frac{I_{MPP}}{I_{SC}}\right)} \tag{3}$$

Coefficients $C_1$ and $C_2$ depend on the following module parameters:

- Short circuit current $I_{sc}$;
- Open circuit voltage $V_{oc}$;
- Maximum power point voltage $V_{MPP}$;
- Maximum power point current $I_{MPP}$;

Such parameters can be expressed as follows:

$$I_{SC}(G,T) = I_{SCS}\frac{G}{G_S}[1 + \alpha(T - T_S)] \tag{4}$$

$$V_{OC}(T) = V_{OCS} + \beta(T - T_S) \tag{5}$$

$$I_{MPP}(G,T) = I_{MPP}\frac{G}{G_S}[1 + \alpha(T - T_S)] \tag{6}$$

$$V_{MPP}(T) = V_{MPPS} + \beta(T - T_S) \tag{7}$$

where parameters $I_{scs}$, $V_{ocs}$, $V_{mpps}$, and $I_{mpps}$ are specified at standard conditions, STC ($G_s$=1000 W/m$^2$ and $T_s$=25 °C) and $\alpha$ and $\beta$ are respectively the current and voltage temperature coefficient; all the above parameters are available on manufacturer's module datasheet. The parameters applied to currents depends on solar irradiance $G$ and temperature $T$, while voltage ones depends only on temperature.

A correction term, $\Delta V(G)$, taking into account voltage variation as a function of solar irradiance is used to improve the accuracy of the model by modifying expressions (5) and (7).

$$V_{OC}(G,T) = V_{OCS} + \beta(T - T_S)\text{-}\Delta V(G) \tag{8}$$

$$V_{MPP}(G,T) = V_{MPPS} + \beta(T - T_S) - \Delta V(G) \tag{9}$$

Correction term $\Delta V(G)$ is obtained by the following relationship:

$$\Delta V(G) = V_{OCS} - V_{OCm}$$

where voltage $V_{OCm}$ represents the open circuit voltage of the $I$–$V$ curve translated from STC to the irradiance $G$ under consideration and is defined as:

$$V_{OCm} = C_2 V_{OCS} \ln\left[1 + \frac{(1 - I_t/I_{SCS})}{C_1}\right]$$

$I_t$ is the short circuit current at irradiance $G$ and can be written as

$$I_t(G) = I_{SCS}\frac{G}{G_S}$$

To determine the value of series $R_s$, as a function of specified parameters, it is convenient to express the module voltage as function of current by inverting Eq. (1):

$$V_P = C_2 V_{OC} \ln\left[1 + \frac{(1 - I_P/I_{SC})}{C_1}\right] \tag{10}$$

The value of series resistance $R_s$ can be calculated by derivative of Eq. (10) with the current $I_p$=0:

$$-R_S = -\left.\frac{dV_P}{dI_P}\right|_{I_p=0} = \left(C_2\frac{V_{OC}}{I_{SC}}\right)\left(\frac{1}{1 + C_1}\right) \tag{11}$$

*4.1.1. Model simulation and results:*

The behavior of PV model has been simulated, in Matlab environment, considering the parameters, at STC, of Photo watt PW75-21V panel enumerated below:

- $I_{sc}$=5 A
- $V_{oc}$=21 V
- $V_{mpp}$=74 W
- $I_{mpp}$=4.5 A
- $\alpha$=1.46 mA/°C
- $\beta$=−158 mV/°C

The model is used to obtain characteristics under different operating conditions for various values of temperature and solar irradiance. Fig. 2 shows $I$–$V$ curves for various solar irradiances

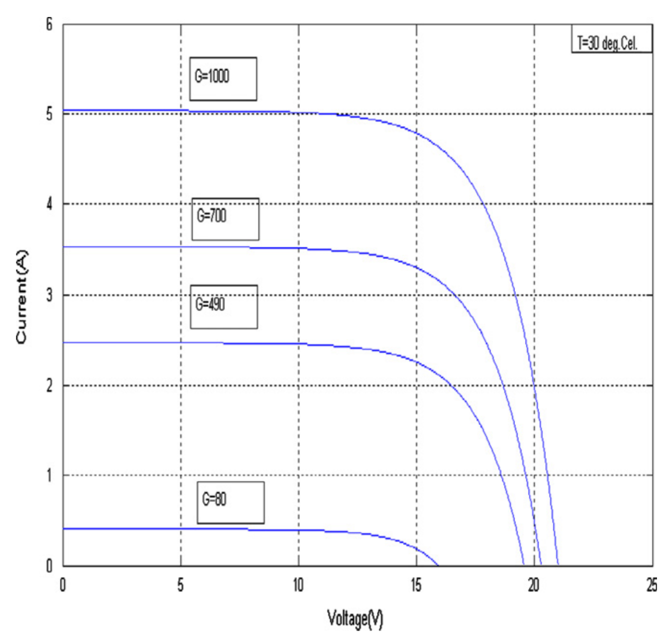


**Fig. 2.** $I$–$V$ curves obtained by simulation of model[8] for various irradiance values.

($G$ various from 80 W/m$^2$ to 1000 W/m$^2$), while Fig. 3 illustrates *I–V* curves for different temperature values ($T$ varies from 25 °C to 35 °C). The power curves are as shown in Fig. 4.

It is possible to notice that, in all the three cases, the trend of the three curves present a similar shape without any significant discrepancy; therefore in the successive implementation and comparisons the proposed model will be used.

### 4.2. *Interpretation of PV module as Norton's circuit:*

The comparison of simulation results of the model mentioned above and the experimental results of the panel when tested shows little difference in the parameter values given on the datasheets supplied by the manufacturer. In consideration of these variations $R_{sx}$ and $R_{px}$ are used to modify the model as shown in Fig. 5.

The values of $R_{sx}$ and $R_{px}$ are determined using the following equations respectively.

$$R_{SX} = \left.\frac{\Delta V_E}{\Delta I_E}\right|_{V_{oc}} - R_S$$

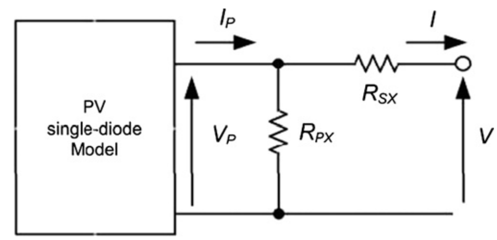


**Fig. 5.** Modified model of PV cell.

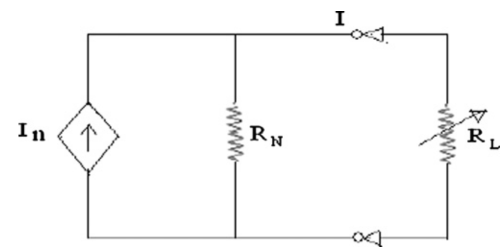


**Fig. 6.** Representation of PV module by Norton's circuit.

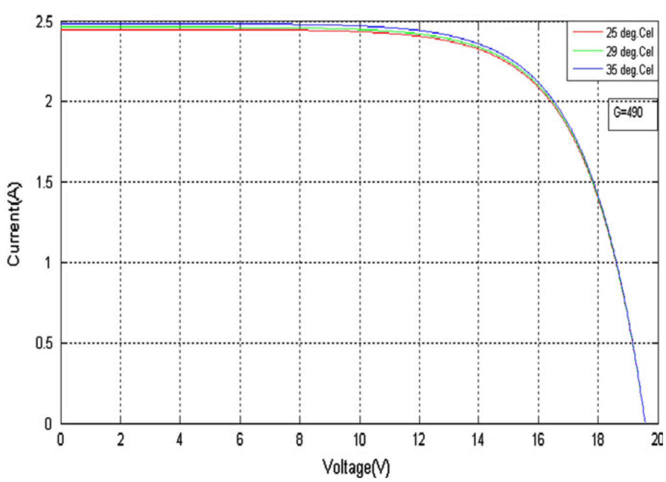


**Fig. 3.** *I–V* curves obtained by simulation of model[8] for various temperatur values.

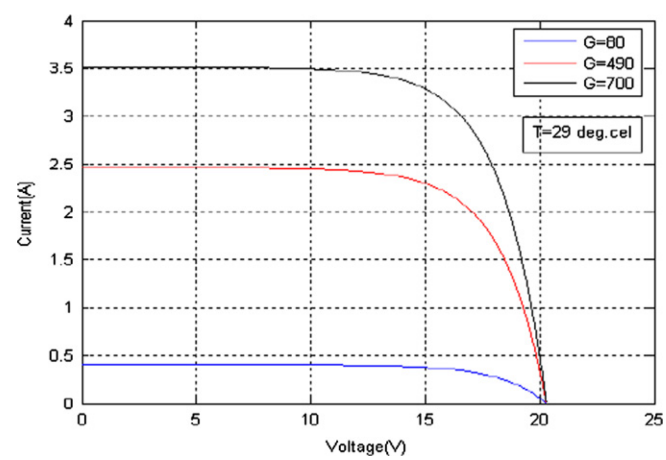


**Fig. 7.** *I–V* curves obtained by simulation for Norton's circuit representation for various irradiance values.

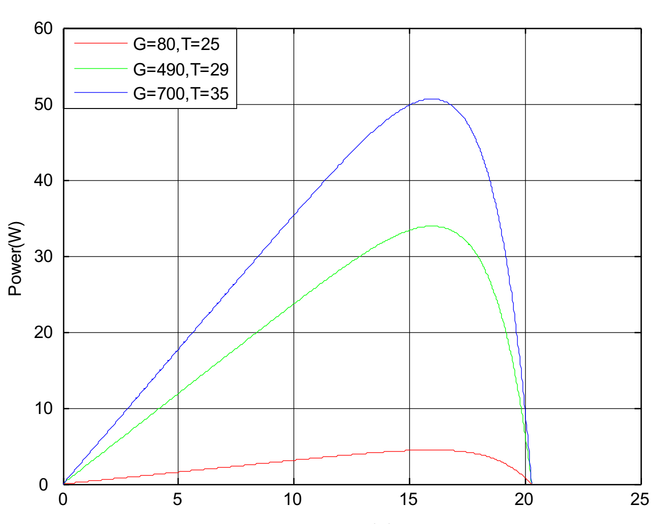


**Fig. 4.** Power curves obtained by simulation of model [8] for various irradiance and temperature values.

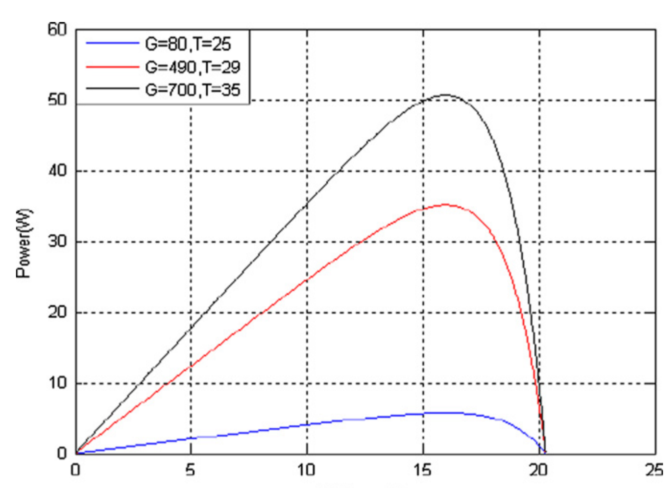


**Fig. 8.** Power curves obtained by simulation for Norton's circuit representation for various irradiance values.

**Fig. 9.** Solar panel arrangement and experimental set up.

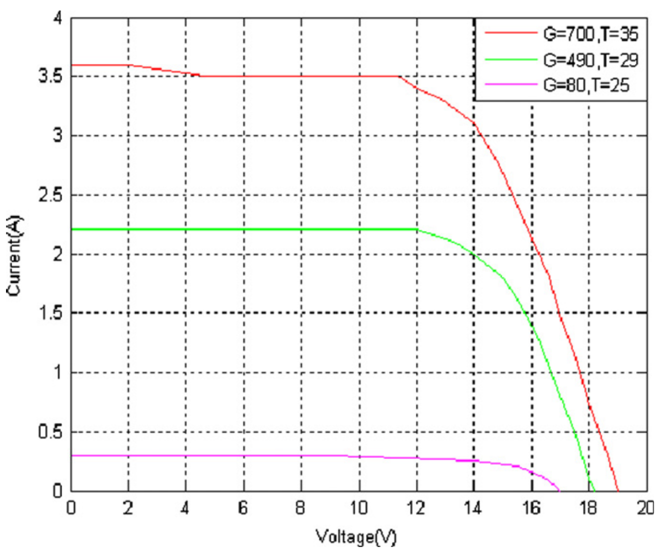


**Fig. 10.** *I–V* curves obtained by experiment for various irradiance and temperature values.

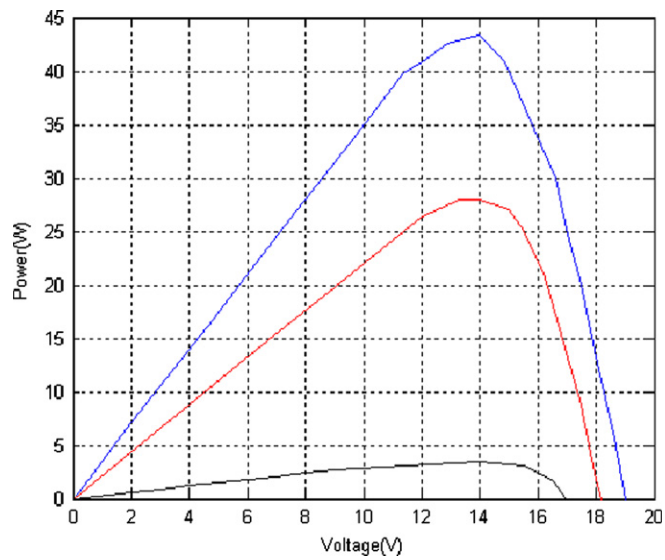


**Fig. 11.** Power curves obtained by experiment for various irradiance and temperature values.The values of powers for differnet models have been obtained and shown if Fig. 12 for comparison.

$$R_{PX} = \left.\frac{\Delta V_E}{\Delta I_E}\right|_{I_{SC}}$$

The output current $I$ is given of the model is given by

$$I = I_P - \frac{V_P}{R_{PX}}$$

And the output voltage $V$ of the model is given by

$$V = V_P - R_{SX} I$$

The model now is consisting of a current source having a resistance in parallel with it and a series resistance. The PV module shown in Fig. 5. can be represented as Norton's circuit across load terminals by computing Norton's (short circuit) current $I_N$ between the load terminals along with the effective resistance $R_N$. The Norton's current is considered as a dependent source and is depending on both irradiance and temperature. Further the characteristics are obtained by simulation at the terminals of the module represented as Norton's circuit shown in Fig. 6.

The Norton's current and the effective resistance at the terminals are computed using the following equations.

$$I_N = I_P \left[ I_P \frac{R_{PX}}{R_{PX} + R_{SX}} \right]$$

and

$$R_N = R_{PX} + R_{SX}$$

This model is simulated using Matlab and the characteristics of the PV cell for different irradiance and temperature values are obtained and are as shown in Fig. 7.

Further the power curve for different irradiance and temperature are also plotted and is shown in Fig. 8. When compared with the model simulation mentioned in first stage the values are almost matching. Thus a Norton's equivalent circuit can be used to give an approximate model of a PV module.

## 5. Experimental set up and results

Several observations have been made by conducting tests on PW75-21 polycrystalline photovoltaic module located on the roof of electrical engineering department. The module has been exposed to the real environment. It is mounted with east oriented frame without tilt arrangement (untracked). The solar panel arrangement and 0065perimental set up is shown in Fig. 9.

The untracked arrngement is chosen because when it is proposed for rural electrification, it is aimed to operate with minimum attention. However, for study purpose the characteristics are obtained for different irradiance values. The irradiance

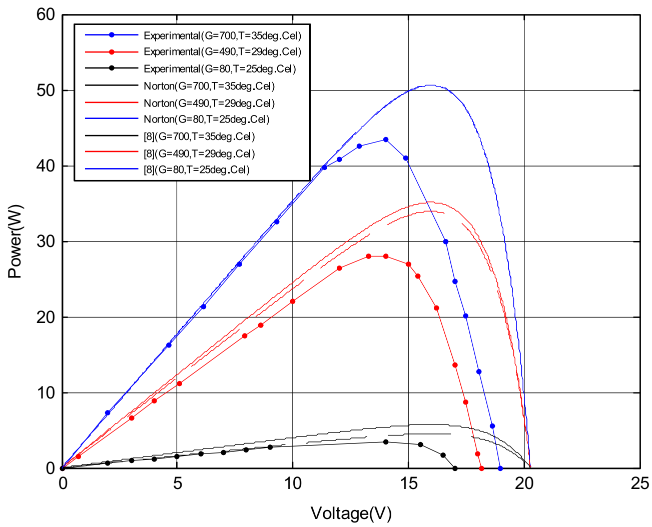


**Fig. 12.** Power curves for different models for variuos values of irradiance and temeprature.

values are used from the generic information in the locality. The module terminals are brought inside the laboratory by means of flexible wires having very low resistance. The experimental set-up consists of ammeter and digital voltmeter calibrated to our lab standards with accuracy limit of +/−5%, battery for charging and lamp load arrangement. A set of readings for different irradiance and temperature values are taken to plot the characteristics and are as shown in Figs. 10–12.

## 6. Conclusion

The curves plotted for performance evaluation in all the three cases viz model [8], Norton's circuit model by simulation and experimental results reveals that there is very close matching of different parameters with number of variants. Further, there is no significant differences in the performance parameters. This asserts that Norton's circuit model is yet another way of representing PV module and thus helps in knowing the terminal behavior and parametrs evaluation. This is a well suited way to evaluate the behavior of PV module that is in operation for long period.This is very much evident from the characteristics drawn for all the three cases. Hence, Norton's circuit model is yet another effective tool to evaluate the performance of a PV module.

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